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ISSUES IN CANADIAN GEOSCIENCE

Tectonic and Magmatic Processes in Crustal Growth: A Pan-Lithoprobe Perspective

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INTRODUCTION

Lithoprobe faces one of its greatest challenges in synthesizing information from 10 transects, acquired over two decades by hundreds of scientists, and published in more than 1500 articles. To foster this process, Lithoprobe is sponsoring a series of thematic workshops designed to bring together workers from different transects to focus on progress made on topics of global interest.

The first Pan-Lithoprobe workshop was held in the autumn of 1999, resulting in a compendium of current views on crustal growth. The 65 participants were encouraged to synthesize relevant information across traditional Lithoprobe transect boundaries, to seek common as well as contrasting threads among young and old rocks, and to provoke discussion on tectonic and magmatic processes involved in crustal growth, destruction, and recycling.

There is still no better guide to crustal growth processes than that articulated by James Hutton more than two centuries ago, that the present is the key to the past. As ideas on modern tectonics evolve, so too does understanding of formation of the ancient crust. However, James Hutton may not have realized a corollary of his philosophy, having seen only about the last 400 million years of the geological record: that we can better understand processes operative on the present Earth by charting their progress through an order of magnitude longer time span. As stewards of a four-billion-year record of continental growth, the Canadian earth science community has advanced understanding of crustal evolution through decades of research, including the accelerated pace of the past 15 years provided by Lithoprobe.

The workshop was structured to explore crustal growth increments during a typical orogenic cycle extending from rifting, through arc magmatism, to collision. The final session considered trends in crustal evolution through geological time. Several workshop experiments were attempted to foster synthesis. Abstracts (see Percival *et al.*, 2000) were posted on a Web site, and pre-meeting discussion encouraged. Oral presentations during the workshop were limited to 10 minutes, with equal time dedicated to discussion. The Web site remained active during the meeting, with periodic updates posted, and discussion from external participants was encouraged. All of these factors, in addition to the enthusiasm of the participants, contributed to producing a stimulating and productive meeting.

MAFIC MAGMATISM AND RIFTING

The Canadian Shield presents a natural laboratory for the study of ancient rift sequences and related mafic magmatism (Fig. 1). Recent discoveries of Archean rift sequences in the Slave and Superior provinces and Baltic shield have been interpreted to record early (*ca.* 2.8 Ga) continental breakup driven by plume magmatism. Studies of the distinctive quartz arenite-carbonate-BIF-komatiite-tholeiite stratigraphy and "fingerprints" provided by detrital zircon populations may supply the information needed for future efforts at Archean plate reconstruction. The widespread distribution of Archean rift packages, along with the common occurrence of oceanic plateau basalts in greenstone belts as old as 3.5

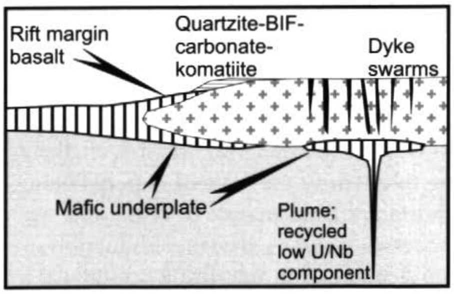

Figure 1 Crustal growth through mafic magmatism. Mantle-derived magmas are extruded onto and underplated beneath continental margins. Plumes impacting on continental crust add material in the form of gabbroic underplates and mafic dyke swarms. Subducted oceanic or continental material may be recycled through the deep mantle as a component of plume magmas.

Ga, provide possible evidence that plume magmatism was more common during the Archean than in subsequent times. However, large igneous provinces, one of the hallmarks of Phanerozoic plume magmatism, have been recognized only as far back as 2.5 Ga, in the form of dyke swarms. Thus, whether plume magmatism dominated the heat loss budget in the Archean, as opposed to spreading ridge volcanism, remains an open question.

Radiating dyke swarms of Proterozoic age are common features of the Canadian Shield, representing plume-related large igneous provinces. Many appear related to rifting, although tests to distinguish a supercontinent breakup event, in which magmatism would be represented in all the fragments, from a global plume event, have proven difficult to formulate. Evidence for the second hypothesis comes from a widespread 2.45 Ga large igneous event that is accompanied by changes in paleomagnetic intensity and atmospheric conditions.

As well as directly transferring material from mantle to crust, mafic magmatism may have second-order effects. For example, subduction of oceanic plateau sequences produced during the Cretaceous resulted in enhanced arc and back-arc magmatism. Major plume events in the past may have led to crustal growth peaks recognized in the geological record at *ca* 2.7, 1.8, and 1.1 Ga.

Arc Magmatism and Crustal Growth

Magmatic arcs are traditionally viewed as sites of crustal growth, and many models regard consuming margins as the main factories of continental crust production. However, even in active arcs it is challenging to quantify the mass of material being transferred from mantle to crust, and processes such as sediment subduction and delamination that bring crustal materials to depth and are recycled through subduction zone magmatism (Fig. 2). In general, a spectrum of magmatic products exists in modern and ancient arcs, from purely mantle-derived material, to rocks generated entirely from pre-existing crust.

Arc roots are complex zones of mixing, magmatic fractionation, and homogenization. These processes result in a layered structure within modern island arcs, which may represent an analogue for various arc types. Continental arcs, built on older crust, are thicker and involve more-complex mixing processes, particularly in long-standing arcs such as the Andes and Grenville Province, which occupied an upper plate setting from *ca* 1.8 to 1.3 Ga. Mixing generally obscures the composition of mantle-derived magmas, but it is important to understand the degree of sub-crustal enrichment in arc basalts in order to estimate the amount of crustal growth.

Igneous charnockites (pyroxene-bearing granite, granodiorite) form a common component of 2.75-1.85 Ga continental arc suites. Their parental calc-alkaline magmas were hotter and less hydrous than younger equivalents, reflecting hotter mantle conditions. Large anorthosite complexes, common within the Grenville Province, appear to be derived by fractionation of mixtures of basaltic magma and lower crustal granulites.

Several factors in addition to suprasubduction zone setting contribute to the generation and emplacement of arc plutons. Pulses of calc-alkaline magmatism in the Cordillera may result from periodic production (*e.g.*, subduction of sedimentary material), or intermittent tapping of deep crustal magma chambers. Emplacement of granitoid rocks can commonly be linked to crustal deformation, and it is likely that the form of intrusions (tabular *versus* tadpole *versus* dyke swarms) reflects ambient stress conditions.

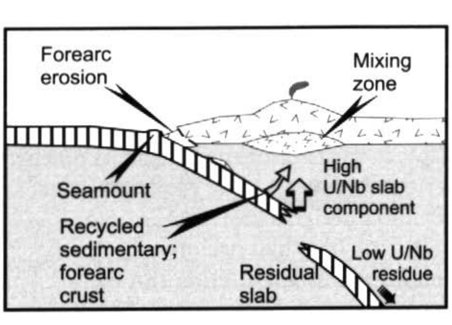

Figure 2 Crustal growth through arc magmatism. Siliceous components are added to the crust by a variety of processes at consuming margins, including slab melting, and recycling of sedimentary and forearc crust.

There was consensus that a uniformitarian approach is required to make progress in understanding the significance of different types of magmatism. Most workers were comfortable with the application of principles and discrimination techniques developed for Recent magmatism to old terranes. Without these tools and assumptions, understanding of the tectonic setting of ancient magmatic rocks would be severely limited, and reconstruction of the tectonic history of Precambrian terranes consequently hampered.

Assuming that uniformitarian principles apply, it is possible to query the geological record for information on temporal differences in magmatic products. Therefore, much effort has been expended to determine the significance of rock types more abundant in the Precambrian than today: komatiites, anorthosites, sanukitoids, charnockites. There is general consensus that early Earth's mantle was hotter than today's, but whether it was sufficiently hot to cause radically different behaviour, such as chaotic mantle turnover and random plume breakout as opposed to organized mantle convection, is still debated. It is possible that the decline in mean mantle temperature over geological time can be monitored through geochemical parameters present in magmatic rocks, and there is potential for further understanding of Earth evolution through modelling igneous processes in different temperature regimes.

Modern settings provide a valuable template for understanding recycling in the ancient record. The Andes represents an appropriate analogue for Precambrian terranes lacking accretionary prisms, a characteristic that applies to most provinces of the Canadian Shield. Conclusions drawn from the Andes, such as the minimal contribution that slab melts make to the magmatic record, need to be reconciled with the large volumes of tonalite-trondhjemite-granodiorite (TTG) of inferred slab derivation, that are present in many Precambrian provinces.

In order to project conclusions regarding the paucity of mass recycled in present subduction zones into the past, changes in the Earth's thermal structure need to be considered. In particular, would warmer mantle temperatures have inhibited eclogite production and therefore forced shallow subduction? Consequences for magmatism might include more direct slab melting, but what would be the ultimate fate of subducted slabs?

The solution may lie in warmer oceanic slabs in the young Earth. The subducted-sediment contribution to arc magmatism is small (1-2%) in well-constrained modern examples, and this process is unlikely to have been materially different in the past. Lower-crustal mixing zones represent probable environments for mantle-derived rocks to inherit continental isotopic and other geochemical signatures.

A conceptual distinction may be made between *recycling*, in which crustal components return to the crust through the mantle, and *reworking*, where crust is melted and reconstituted through heat input, but without mass transfer from the mantle. It is challenging even in active systems to determine the relative importance of these processes in the generation of particular rock suites, and particularly difficult in ancient, long-standing margins.

ACCRETIONARY TECTONICS AND CONTINENTAL GROWTH

Many Lithoprobe lines crossing orogenic crust feature subhorizontal panels of reflectivity on a 10-km scale that have been interpreted as evidence for thin-skinned stacking of crustal slices. These features have given rise to the hypothesis that oceanic material has become incorporated into continental margins by overthrusting (obduction) or underthrusting (tectonic wedging) (Fig. 3). Many deep crustal reflectors cannot be traced to the surface, and thus these interpretations can be challenged. Also plausible for the reflective packages are subhorizontal ductile shear zones, including possible late structures that have reoriented earlier steep faults.

There was no debate, however, that plate collision processes have produced mountain ranges and compensatory crustal roots in Phanerozoic orogens. It is therefore puzzling that the Moho topography of shield regions is characteristically flat. Reconciliation appears to lie in ductile flow of the lower crust, which accommodated orogenic collapse. Some deep crustal xenoliths in kimberlites carry zircon age evidence for this late tectonic adjustment, whereas others attest to the presence of much younger magmatic underplating, in most areas coeval with high-level mafic dyke swarms.

Perhaps the best examples in the ancient record of oceanic fragments trapped between continental blocks come from the Trans-Hudson orogen (1.80 Ga) and western Superior Province (2.70 Ga). These regions house juvenile terranes exotic to the older blocks, but the geometry of their juxtaposition differs. Whereas vertical stacking is apparent from geophysical, isotopic, and structural evidence in parts of the western Trans-Hudson orogen and southwestern Superior Province, other parts of the Trans-Hudson and northwestern Superior have vertical terrane boundaries more akin to those of modern strike-slip margins.

Crustal gains through transfer of material from oceans to continents appear to be more or less balanced by losses through subduction erosion on the global scale at the present time. Examples from the Andes demonstrate 600-700 km of forearc loss during 245 m.y. of convergence and recurrent continental arc magmatism. These processes may have been particularly active in the past based on the nature of widespread arc magmatism and lack of forearc sequences, including accretionary prisms, in the Precambrian record.

Although not directly related to crustal growth through accretion, an outstanding issue that arose in discussion concerned the fate of subducted crustal material: does it remain permanently in the mantle, or return to the surface in ocean island basalts through the operation of plumes (Figs. 1, 2)? There is some evidence of the latter process, as far back as the Archean. There was general agreement that crustal gains and losses are approximately in equilibrium in the modern framework. However, this is not instructive with respect to assessing growth in the past because the Earth may be in a steady-state phase at present. The most critical windows are the "growth peaks" at 2.7 Ga, 1.8 Ga and 1.1 Ga. Establishing the extent of growth and recycling during these well-preserved parts of the record is key to resolving the age-old debate regarding whether the volume of continental crust has grown over geological time.

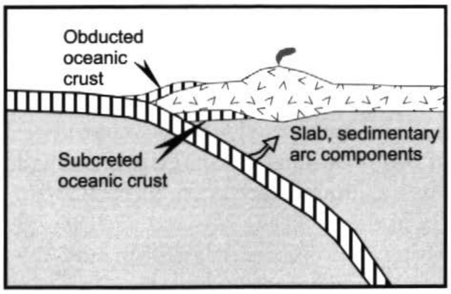

Figure 3 Crustal growth processes at accreting margins. Slabs of oceanic crust or juvenile arc terranes may be obducted or subcreted at convergent margins. Not shown is strike-slip accretion of similar oceanic objects.

CONTINENTAL COLLISION TECTONICS AND MAGMATISM

Progress in understanding crustal growth hinges on our ability to "see through" the effects of deformation, metamorphism, and intracrustal melting events superimposed during orogenesis. Indeed, distinguishing newly accreted material from older crust within a sea of migmatites is a challenging objective. Yet studies of modern orogens reveal that many insights are buried within orogenic hinterlands (Fig. 4). The deeply eroded internides of Precambrian orogens may thus bring to light features observed only remotely within younger terranes. One tool that has been used successfully in high-grade terranes is the neodymium model age

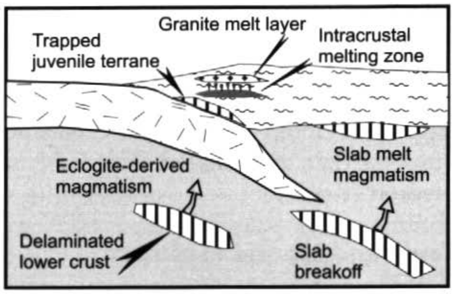

Figure 4 Aspects of crustal growth in collisional orogens. In addition to oceanic terranes trapped within sutures, material may be added through magmatic processes driven by delamination or slab breakoff. Following erosion to mid-crustal levels, the effects of deformation, metamorphism and intracrustal magmatism commonly obscure original relationships.

mapping technique. This means of distinguishing juvenile from evolved crust has served as a guide to locating possible cryptic sutures in parts of the Grenville and Superior provinces.

Papers in this session illustrated aspects of the intimate feedback relationships between crustal growth and orogenic evolution. The character of accreted material (extinct *versus* active arc; radioactive sediments, *etc.*) influences the crustal temperature profile, as does the position within the orogenic margin (fore-arc; arc; back-arc). These factors determine the rheology of the lithosphere, which in turn controls the tectonic style: thick-skinned *versus* thin-skinned. The Tibetan plateau may represent an analogue for ancient low-pressure, high-temperature metamorphic terranes in that a melt-rich layer appears to be present at 10-20 km depths within a 70-km thick crustal column. Much of the strain associated with the dynamically supported topography is accommodated by flow within this weak layer.

Feedback between tectonics and magmatism is apparent at a variety of scales. The orientation of foliation, for example, determines melt-flow pathways during high-grade metamorphism; heat advected in this process softens higher crustal levels, which are then more prone to deformation. The generation and emplacement of syn-tectonic plutons has been linked to sites of active deformation.

Although not traditionally considered as sites of juvenile magmatic additions, mafic rocks in deeply exhumed collisional zones such as the eastern Grenville Province have been linked to coeval compressional deformation and tectonic extrusion. Processes involved in production of these magmas are enigmatic but may relate to delamination or slab breakoff (Fig. 4).

Crust and Mantle Evolution

This session focussed on questions that were sub-themes of the previous topics: how have Earth processes evolved over geological time; and a corollary, was the Archean fundamentally different from the modern tectonic regime? It has long been recognized that many of the hallmarks of plate tectonics are absent in the Archean record: obducted oceanic crust, tectonic mélanges, high-level thrust belts, accretionary wedges, foreland basins, and low-temperature/high-pressure metamorphic belts. However, the significance of these observations continues to be debated.

One argument in favour of a non-plate tectonic regime for the Archean is the presence in some greenstone belts of the northwestern Superior Province of a 250 m.y. stratigraphic record, apparently unbroken by tectonic upheaval. Modern analogues for such a long-standing arc-like regime cannot be cited. However, it is not clear whether a fundamentally different (*e.g.*, plume-driven) tectonic framework is required to explain these differences, or if some modified form of plate tectonics was operating.

Geochemical studies of Archean plume-related basalts shed some light on this question. Based on trace element ratios such as Nb/U, it can be argued that plume sources contain recycled oceanic and continental material, possibly in the form of slab residues subducted to basal mantle depths (Fig. 2). Secular changes in the composition of the mantle are apparent from comparison of major element contents of Archean and younger basalts. Richer in iron and poorer in aluminum, the Archean mantle may have been closer to chondrite than primitive mantle in its bulk composition.

Changes in the mantle may be reflected in subtle differences in the structure and composition of the crust over geological time. Archean lithosphere is thicker and its crust somewhat thinner and more mafic than Proterozoic analogues, possibly a function of declining mantle temperatures that permitted eclogite transformation and lower crustal delamination in the younger terranes. Present heat flow appears independent of lithosphere age, as there is more variation within age provinces than between them.

Based on the geological record, Earth's fundamental tectonic framework of continents and oceans existed throughout the Proterozoic and as far back as 3 Ga in the Archean. Processes such as rifting, drifting, arc magmatism, and terrane amalgamation have been recognized in the Archean Superior and Slave provinces. Ancient arc systems are not greatly different from the Cambro-Ordovician oceanic arc sequences preserved in the central Newfoundland Appalachians.

In summary, while diverse types of data point to some form of plate tectonics in the Archean, there are still alternate models being considered to explain the Earth's early tectonic evolution. Geochemical data, although permissive of an Armstrong-style early formation of continental crust, do not require it. The question of the rates of formation and destruction of oceanic crust remains very much open.

CONCLUSIONS

Many magmatic and tectonic processes of crustal growth and recycling appear well understood, although important questions remain. Using the present as the key to the past has improved our understanding of the setting of magmatism in orogens of Cenozoic to Precambrian age. However, if Warren Hamilton's (1998) emphatic statement, that "Archean magmatism and deformation were not products of plate tectonics," has any validity, then a new framework is required to explain remarkably similar magmatic products and tectonic histories. Resolution of this debate must come from comparative field-based studies involving integrated high-resolution geochronology, geochemistry, petrology, and structural analysis. Related to this question is the problem of the nature and variability of mantle reservoirs in the past. Although some reservoirs appear similar to those recognized in the modern record (depleted; metasomatized; enriched), others (Fe-, Si-rich) may have no analogue. The implications for derivative rocks of Fe-, Si-rich primitive magmas warrant further examination.

The crustal growth theme represents one of several identified (Percival *et al.*, 1999) as key to the Pan-Lithoprobe synthesis, which is the natural conclusion of a program that has at its heart the integration of diverse geoscience information into a coherent 4-D picture. Additional workshops were held in 2000 (Where crust meets mantle: Lithoprobe perspectives on the continental crust–mantle boundary; Lithoprobe, 2000) and 2001 (Mantle lithosphere and Lithoprobe: Views of continental evolution from the bottom up; Beaumont *et al.*, 2001), and a final meeting is being planned for early in 2003 (Orogen Reconstructions and Comparative

Orogenic Anatomy). The entire community is being asked to contribute to the task of integration in bringing the Lithoprobe synthesis to fruition.

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